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Life cycle assessment of common carp (*Cyprinus carpio* L.) – A comparison of the environmental impacts of conventional and organic carp aquaculture in Germany

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ABSTRACT

The steadily growing aquaculture industry has been blamed for increasing environmental impacts at local and global levels. The greatest increase in production is expected for freshwater fish, such as carp and related species. Decisions on sustainable environmental management strategies in aquaculture should be based on quantitative analyses of their environmental impacts.

In this study, Life Cycle Assessment (LCA) methodology was employed to compare the environmental impacts of conventional and organic common carp (*Cyprinus carpio* L.) raised in traditional pond aquaculture. Data collected in personal interviews with carp farmers in southern Germany was used for inventory analysis. Interviews with farmers showed that in practice, the key difference between organic and conventional production of carp lies in the sourcing of feed grains from certified organic versus conventional origin.

The results of the impact analysis showed that conventional carp production has higher indicator values for climate change, ozone depletion as well as ionizing radiation (human health) and uses more water resources. Organic production led to higher acidification and an increase of over 100% in marine and terrestrial eutrophication compared to conventional production. Independent of the production system, feed and pond dredging (i.e., the effort of sludge removal from the pond using machinery) were the main contributors to many of the impact categories, apart from freshwater eutrophication, which was largely dependent on the carp farming stage. Therefore, the environmental superiority of one production method over the other depends on the impact category analyzed. A comparison with previously published LCAs of fish and meat products for the impact category of climate change shows that both, conventional and organic carp, have significantly lower indicator values than products from recirculating aquaculture systems or terrestrial animal products, such as beef. This finding, as well as the retention functions and ecosystem services provided by carp ponds, contribute to the environmental sustainability of both forms of carp aquaculture studied.

Further efforts to increase the systems' sustainability should target the key areas of feed type and amount, frequency and method of pond dredging as well as the nutrient retention rate of carp, affecting potential emissions during harvest. Moreover, carp products with organic certification, wanting to uphold their claim of superior environmental friendliness, should address the critical issues uncovered in this LCA. Continuing methodological development, which acknowledges aquaculture specific impacts, will further increase the applicability of LCAs for products from aquaculture.

1. Introduction

Aquaculture production has steadily increased in response to the combined effects of an increasing market demand for fish by a growing world population and a stagnating production volume from capture fisheries (e.g., Ayer et al., 2009; Naylor et al., 2009; Pelletier et al., 2007). Between 2010 and 2014, world aquaculture production grew by an average of 5.8% annually (FAO, 2016a). The growth of aquaculture production can lead to increasing environmental burdens, such as the eutrophication of water bodies, the introduction of invasive species, parasites, and diseases to wild populations, an increasing dependence on fishmeal and oil as feed, the use of antibiotics and chemicals, as well as emissions contributing to climate change (e.g., Ayer and Tyedmers, 2009; Henriksson et al., 2011; Pelletier et al., 2007). These

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circumstances call for sustainable environmental management strategies in aquaculture, which should be based on environmental impact analyses.

Fish in general have certain advantages over meat products for human protein supply, such as providing unsaturated fatty acids, vitamins, and minerals. The common carp (*Cyprinus carpio* L.), as an omnivorous freshwater fish, adds additional environmental friendliness to the equation: It can be produced without the use of fishmeal or oil, in contrast to predatory fish species, such as trout or salmon (FAO, 2015; Hoole et al., 2008). Due to its broad ecological spectrum, it can furthermore be produced close to the point of sale. In contrast to new high-tech solutions, such as recirculating aquaculture systems (RAS), carp pond farming is the oldest known form of European aquaculture (Balon, 1995; Martins et al., 2010). A rather new development in this traditional sector of aquaculture is the introduction of eco-certification for sustainable and – even more restrictive – organic fish farming (Cooke et al., 2011).

While the production volume of carp in Germany, with 5200 t in 2014, is miniscule compared to the global production volume of 4.2 million tonnes (FAO, 2016a), Germany is currently Europe's fourth largest producer of carp, after Poland, the Czech Republic, and Hungary (FEAP, 2015). However, carp production has continued its declining trend in Germany by 7% between 2013 and 2014 (Brämick, 2014). This development is mainly due to predation by protected wildlife (cormorants, great egrets, and otters), increasing cost, less subsidy payments, and consumer preference for carnivorous finfish, such as trout or salmon.

While in public discourse organic farming is often named as a solution to reducing impacts on the environment, such statements are often times not based on sound scientific evidence (Tuomisto et al., 2012). Currently, both Greenpeace and WWF list common carp as the only fish species recommended for consumption, irrespective of the production region and method (Greenpeace, 2016; WWF, 2016), but the environmental assessment basis of this classification is not reported. With an aim to reach sustainability goals in aquaculture production, advantages and disadvantages of systems and their sub-processes need to be assessed and made apparent according to scientific standards.

Life cycle assessment (LCA) methodology can be used to quantify and compare the environmental impacts of product systems throughout their lifecycle (ISO, 2006). The unique strengths of the method lie in (1) its ability to address a wide range of environmental issues and include the entire life cycle of a product, thereby avoiding problem shifting, (2) its scientific and quantitative approach, and (3) its ability to allow for product or service comparisons by employing a common functional unit. LCA was originally developed for industrial products, but has since been applied to other areas, with the first LCAs of food products, focused on primary energy demand, carried out in the 1970s (Nemecek et al., 2016). The number of LCA studies in the area of agriculture has increased manifold and, since the mid 2000s, the method has also been applied to products from aquaculture (Avadí and Fréon, 2013). More recently, LCA has been used to also compare organic and conventional production methods (Meier et al., 2015). However, in the area of aquaculture, to the best of our knowledge, only two such case studies have been published in peer-reviewed literature: a comparison of conventional and organic production of shrimps (Jonell and Henriksson, 2015) and ingredient types in salmon feeds (Pelletier and Tyedmers, 2007). For German aquaculture, Samuel-Fitwi et al. (2013) carried out an LCA of rainbow trout produced in extensive, intensive, and recirculating systems. The environmental impact of carp has, to date and to the best of our knowledge, only been analyzed in an LCA case study of carp and tilapia net cage aquaculture in Indonesia (Mungkung et al., 2013).

The objective of this study was to compare two production systems, which have not been analyzed using LCA methodology until now: conventional and organic common carp, raised in extensive or semi-intensive earthen pond aquaculture, as traditionally practiced in southern Germany and many other parts of Europe. The core objective was to answer the following research questions:

(1) Which system has a greater environmental impact in producing 1 kg of live carp at the farm gate?
(2) Which production processes contribute decisively to the environmental impact and which areas have potential for further improvement in environmental sustainability?
(3) How does the impact of carp compare to other products providing animal protein for human consumption?

The results of this LCA may uncover advantages of either production method and potential for improved environmental sustainability, based on a method accepted in the scientific community.

2. Materials and methods

An LCA is an iterative process that is carried out in four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The subsequent sections are based on the framework as defined by the ISO standards 14,040:2006 and 14,044:2006 and outline the decisions made in each of the four phases (ISO, 2006).

2.1. System description

In southern Germany, carp is traditionally produced in extensively or semi-intensively managed earthen ponds in a three-year-long production cycle, with fish growth taking place mainly in the summertime. The natural food in the pond provides the basis for the growth of carp and is increased through fertilizer application prior to stocking, thereby increasing primary production and the growth of zooplankton and benthic invertebrate biomass, which provide the main source of protein for carp. Carbohydrate-dominated grains such as wheat, barley, triticale, and rye are fed to increase productivity, especially in the third year of production. The majority of the produced table size fish is marketed locally after the third summer.

Organic certification of aquaculture products has been regulated on an EU-wide level since the implementation of the European Commission Regulation (EC) No 710/2009 on 5 August 2009 (Commission Regulation (EC), 2009). Accordingly, the following criteria are required of certified organic aquaculture and therefore, also of organic carp in this study:

- Ponds of natural earth
- Fish harvest area of adequate size equipped with a freshwater inlet
- Areas of natural vegetation around inland water units as a buffer zone for external land areas not managed according to organic regulations
- Use of organic or inorganic fertilizer of up to 20 kg N/ha
- Maximum harvest of 1500 kg/ha/year
- No use of synthetic chemicals to control hydrophytes or plant coverage
- Retention of carp in freshwater after harvest
- Feed from natural supply in pond and supplemented with certified organic feed of plant origin, preferably sourced from the operation itself
- No use of hormones for propagation.

The carp farming systems serve the function of producing carp for human consumption. The functional unit is 1 kg of live carp at the farm gate. The system boundary includes a three-year long carp production cycle from cradle to farm gate (see Fig. 1). The system boundary is set before slaughtering takes place, as no systematic differences for organic and conventional carp, pertaining to the utilization of fish by consumers, are expected and final consumption is not the focus of aquaculture management decisions.

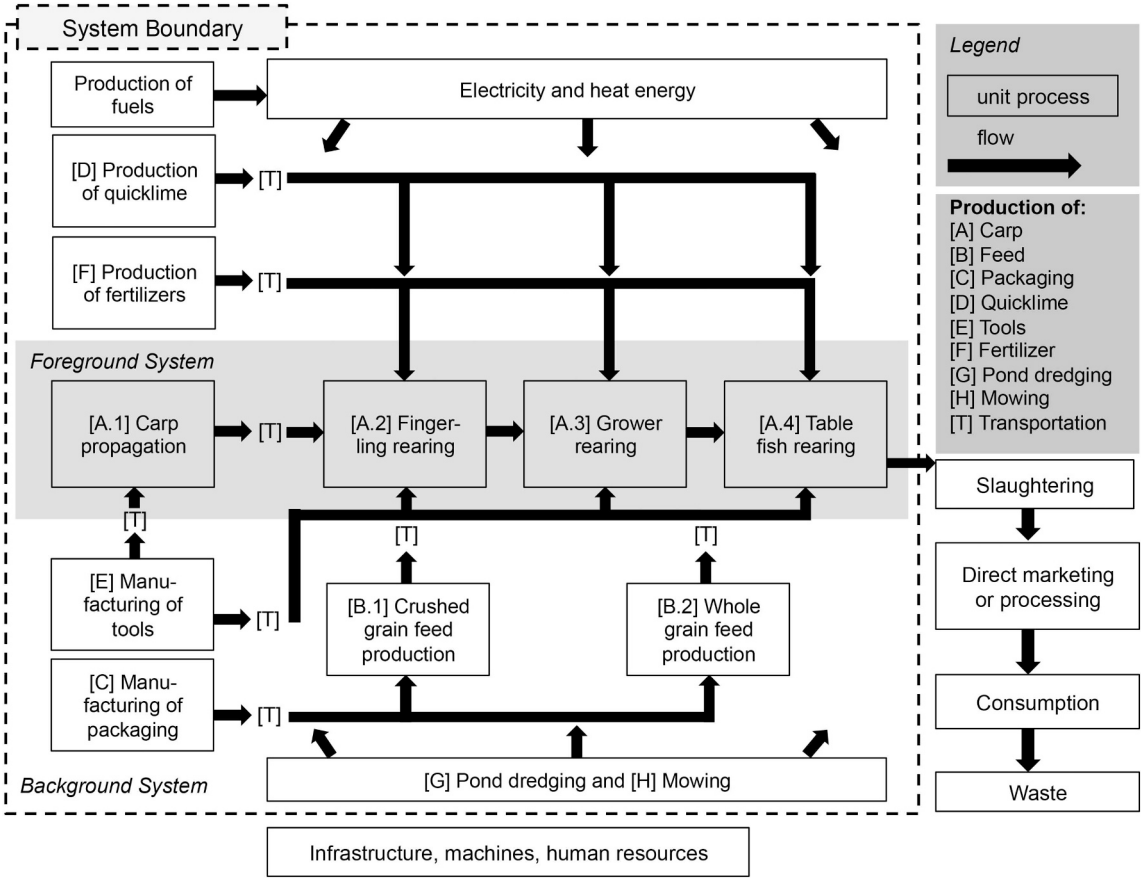

Fig. 1. Process flow diagram showing the system boundaries of the carp supply chain under study.
Note: [D] and [F] were only used in conventional carp farming and scenario analysis, respectively.

For the contribution analysis, the carp aquaculture system was clustered into nine process groups: [A] carp farming, [B] feed production, [C] packaging production, [D] quicklime production, [E] tool usage, [F] fertilizer application, [G] pond dredging, [H] mowing, and [T] transportation.

2.2. Data collection

The inventory analysis for conventional carp was based on the aggregated data of a survey carried out by the Institute for Fisheries of the Bavarian State Research Center for Agriculture, which collected the management practices of a representative sample of 88 Bavarian carp producers (Wedekind et al., 2014). Since most carp production, by total number of farms, is situated in northern Bavaria (Middle Franconia and Upper Palatinate), the majority of responses originate from this region (86%). Data for the organic production system was collected through personal interviews on site in 2016 with certified organic carp farmers in Bavaria, based on recommendations from the Bavarian Institute of Fisheries (Wedekind, pers. comm.). Out of six currently certified organic carp farms in Bavaria, four were interviewed for data collection, chosen for their representativeness of organic carp farming practices in Bavaria. The farms were located in the regions of Middle and Upper Franconia, Upper Palatinate, and Upper Bavaria. An overview of the management practices of carp farmers in southern Germany is shown in Table 1.

These two principal sources of production data were used to model average carp farms of both types, representative for the region. Since farmers were not always able to explicitly provide the amount of feed fed to carp in each production stage, calculations based on the Feed Conversion Ratio (FCR) had to be made to estimate feed amounts. An FCR of 2 kg feed per kg of total weight gain per pond including losses was used in the baseline scenarios, as suggested by literature (Füllner et al., 2007; Hofmann et al., 1987; Schäperclaus and von Lukowicz, 1998). In the survey, only two farmers made use of inorganic fertilizers and over 60% of respondents did not use any fertilizers. This may be due to the economic infeasibility of fertilizer application for Bavarian carp farmers or carp ponds being set in an agriculturally used landscape, where nutrient runoff from surrounding fields may potentially contribute to sufficient fertilization of ponds. Furthermore, the low stocking density currently used in Bavarian carp farming leads to fertilization of ponds being unnecessary in most cases. Use of fertilizers was nonetheless modeled as part of the scenario analysis, since it was considered a possible option for farmers at an increasing market demand, i.e., in order to simulate the effects of an increasing demand of carp on farming practices. Quicklime (CaO) is used by conventional carp farmers to buffer or stabilize pH values, increase pond fertility, and as a preventative measure against parasites. Organic carp aquaculture is modeled without the use of quicklime. Carp are harvested behind the monk and transported in containers filled with freshwater using a water pump powered by a diesel generator. The carp farmers surveyed provided no information on the nutrient load of discharge water. Therefore, a nutrient balance based on P and N retention – defined as the difference between nutrient input through feed and retention by the carp – was used to model pond effluents during harvest. Of the total pond volume, 75% is dredged every 12.5 years on average, with the help of a hydraulic digger.

Carp farming is modeled in the baseline scenario as a monoculture, since less than half of the carp farmers questioned raise secondary fish. Therefore, the baseline scenario does not produce any co-products and no allocation decisions needed to be made. In one of the modeled

Table 1
Management practices of organic and conventional carp farmers in southern Germany.

Inputs and outputs	Average values
Stocking densities	
Carp larvae	90,900 individuals/ha
Carp fingerling	3000 individuals/ha
Carp grower	600 individuals/ha
Harvest weight[a]	
Carp larvae	0.002 g
Carp fingerling	0.037 kg
Carp grower	0.461 kg
Carp table fish	1.47 kg
Survival rate	
Carp larvae	50%
Carp fingerling	73%
Carp grower	88%
Pond size	
Carp larvae	125 m^2
Carp fingerling	1 ha
Carp grower	2 ha
Carp table fish	3 ha
Quicklime[b,*]	100 kg/ha (conv.) 0 kg/ha (organic)
Feed composition[c]	
Barley	2.0%
Wheat	70.5%
Rye	26.5%
FCR[d]	2

* Differences between organic and conventional carp farming are marked with an asterisk.
[a] Harvest amounts are calculated using the following formula: *stocking density [individuals/ha] * pond surface area [ha] * survival rate * harvest weight [kg]*.
[b] Applied every three weeks.
[c] Feed used in organic carp aquaculture is of certified organic origin.
[d] Feed Conversion Ratio (FCR) is calculated using the following formula: *feed [kg]/Δw [kg],* where Δ*w* = total weight gain per pond including losses.

scenarios of conventional carp farming, wheat straw is used as an organic fertilizer. Wheat straw and grain was allocated on the basis of economic value (market prices) instead of mass, following the method employed by Wang et al. (2013). Data for background unit processes were taken from the ecoinvent v3.3 database set to allocation, cut-off by classification and thinkstep GaBi LCA databases. Feedstuff is based on ecoinvent datasets for organic and conventional crops produced in Switzerland, which is similar to German agricultural practices (Bystricky et al., 2014). Adjustments were made to the background datasets "green manure growing, organic, until April" (replacing rapeseed with rye, which is more commonly used in the region) and "transport, tractor" (removing the trailer as input). For details on specific datasets used and adjustments made, the information provided in the supplementary material (Appendix A) can be used in combination with the dataset search functions of ecoinvent (www.ecoinvent.org) and GaBi (http://www.gabi-software.com/international/databases/gabi-data-search). The software GaBi ts version 7.3 was used to model inventory data and carry out the impact assessment.

2.3. Impact assessment

For the impact assessment, the collected elementary flows (i.e., resource consumption and emissions to air, water, and land) were assigned to environmental impact categories and converted into indicators with the help of characterization factors according to the recommendations of the International Reference Life Cycle Data System (ILCD) (JRC-IES, 2010). The ILCD methodology was chosen as it covers characterization factors for impact categories commonly found in studies of food products (e.g., Abdou et al., 2018; Avadí and Fréon, 2013; Castellani et al., 2017; Notarnicola et al., 2017), is furthermore suitable for the European context, and has undergone a rigorous review process by the European Commission's Institute for Environment and Sustainability (JRC-IES, 2011).

The following 14 impact categories were calculated: Climate change (CC) excluding biogenic carbon in kg CO_2-eq, ozone depletion (OD) in kg CFC-11 eq, human toxicity cancer (HT_c) and non-cancer related (HT_{nc}) in CTU_h, particulate matter (PM) in kg $PM_{2,5}$-eq, ionizing radiation (IR_{hh}) human health in kg U^{235} eq, photochemical ozone formation (POF) in kg NMVOC, acidification (AP) in mole of H^+ eq, terrestrial eutrophication (TE) in mole of N-eq, freshwater eutrophication (FE) in kg P-eq, marine eutrophication (ME) in kg N-eq, freshwater ecotoxicity (FE_{tox}) in CTU_e, fossil and mineral resource depletion (RD_{fm}) in kg Sb-eq, and water resource depletion (RD_w) in UBP.

Optional steps of impact assessment include normalization and weighting of impact indicator results (ISO, 2006). In normalization, indicator results are divided by a reference value to better understand the relative magnitude of each indicator and to identify "hot spots". To be able to assess the effects of different reference systems on the conclusions drawn, three ILCD-compliant normalization factors EC-JRC EU27 (Benini et al., 2014; Sala et al., 2015), EC-JRC Global (Benini et al., 2015), and PROSUITE Global (Laurent et al., 2013) were used and compared.

For weighting, the normalized impact assessment results are multiplied by a set of weighting factors. Weighting sets can be clustered into three groups: monetary evaluation, distance-to-target (related to policies or carrying capacity), or based on expert panels (Castellani et al., 2016). Weighting sets therefore reflect a range of scientific standpoints, political views or other value-based judgments and are thereby always normative (JRC-IES, 2010). In contrast to normalization, weighting should therefore not be used for comparative assertions disclosed to the public, according to ISO (2006), and is therefore not part of this study.

2.4. Scenario definition and sensitivity analyses

In order to assess system variations, a sensitivity analysis was carried out for different hypothetical scenarios. All scenarios used the conventional carp farming model as a baseline (Table 2). Even though fertilizer was only reportedly used by 40% of respondents in the survey carried out by Wedekind et al. (2014), the heterogeneity of carp farming practices and the suggestion to use organic fertilizers to increase pond fertility and harvest by carp farming guidebooks, justify the variation of fertilization practices in the form of three scenarios: chicken manure, wheat straw, and rye seeds, as e.g. commonly

Table 2
Fertilization, FCR, and nutrient emission scenarios.

Scenario	Values
Fertilization	
Baseline	-
FS1: chicken manure	1000 kg/ha
FS2: wheat straw	500 kg/ha
FS3: rye seeds as green manure	70 kg/ha
FCR[a]	
Baseline	2
FCRS1	1
FCRS2	5
Nutrient emissions	
Baseline	$P_{emission} = P_{fed} - (P_{fed} * P_{avg.\ retention\ rate})$ $N_{emission} = N_{fed} - (N_{fed} * N_{avg.\ retention\ rate})$
ES1[b]	$P = 4.76\ g\ ha^{-1}$ and $N = 66.7\ g\ ha^{-1}$

[a] Feed Conversion Ratio (FCR) is calculated using the following formula: *feed [kg]/Δw [kg],* where Δ*w* = total weight gain per pond including losses.
[b] Emission values for ES1 are based on values calculated by Knösche et al. (2000).

practiced in Eastern European carp farming. The calculations for the fertilization scenarios do not include additional emissions caused by the use of fertilizers. To further analyze this, follow up studies should evaluate fertilization effects on discharge water in field-based experiments.

Since no exact feed amounts were provided in the study carried out by Wedekind et al. (2014) and feed has been shown to contribute significantly to the environmental impact of aquaculture products (e.g., Henriksson et al., 2011), a sensitivity analysis was carried out to approximate the impact of different FCR values. FCR values were chosen to represent best and worst cases and are based on data from literature (FAO, 2016b).

A potential negative effect of carp pond aquaculture on downstream water bodies has been a topic of ongoing discussion in Germany (Knösche et al., 2000). For this reason, two nutrient emission scenarios were modeled to observe the effect of different calculation principles on the environmental impact. A nutrient balance was used to approximate emissions for the more conservative baseline case and previous scientific research by Knösche et al. (2000) served as the basis for a second emission scenario. It should be noted however that emissions from ponds should be measured in field-based experiments to account for potential influences of surrounding agricultural land and to better consider the influence of different fertilization scenarios in follow-up studies.

3. Results

3.1. Inventory analysis

Interviews with farmers showed that in practice, only minor differences exist between conventional and organic production of carp: To obtain an ecolabel, many farmers solely had to adjust their feed sourcing to certified organic grain. Stocking densities for both conventional and organic carp farming were in practice close to the upper limits set for organic pond aquaculture by national associations for organic agriculture and food processing in Germany, such as Naturland, Bioland, and Gäa (see Table 1): 3000 fingerlings per hectare and 600 growers per hectare (Bioland, 2016; Gäa, 2015; Naturland, 2016). These stocking densities lead to harvest amounts that are almost 50% below the maximum allowed according to EC No 710/2009. An overview of inventory results is shown in Table 3. In-depth information about the data used in the present study is available as supplementary material (Appendix A) provided online.

Table 3
Life cycle inventory for conventional and organic production of 1 kg of carp.

Material and energy inputs	Unit	Conventional (n = 88)	Organic (n = 4)
[A] Carp			
Carp larvae	g	4.2E-03	4.2E-03
Water (rain water)	m^3	2.5E + 01	2.5E + 01
Diesel, burned in diesel-electric generator	kWh	9.5E-03	9.0E-03
N (inorganic emissions to freshwater)[a]	kg	2.8E-02	2.8E-02
P (inorganic emissions to freshwater)[a]	kg	5.5E-03	5.0E-03
[B] Feed			
Carp feed (whole grains); packaged[b]	kg	2.2E + 00	2.2E + 00
Carp feed (crushed grains); packaged[b]	kg	1.2E-01	1.2E-01
[C] Packaging			
Feed sack (PE, PP)	kg	7.5E-03	7.5E-03
Tower silo	m^3	3.9E-04	3.9E-04
[D] Quicklime			
Quicklime, milled	kg	1.4E + 00	–
Fertilizing with tractor (67 kW)	m^2	1.7E + 01	–
[E] Tools			
Tools (plastics, aluminum, lead, fabrics)	kg	2.6E-03	2.6E-03
Tools (steel, shed)	pcs.	3.0E-05	3.0E-05
Tools (irrigation pump)	m^3	1.9E-02	1.9E-02
[F] Fertilizer[c]			
Green manure	m^2	1.7E + 01	–
Poultry manure, dried	kg	1.7E + 00	–
Fertilizing with dung spreader (54 kW)	m^2	1.7E + 01	–
Wheat straw	kg	8.3E-01	–
[G] Pond dredging			
Excavation with hydraulic digger	m^3	4.5E + 00	4.5E + 00
[H] Mowing			
Mowing, by motor mower	m^2	1.2E + 00	1.2E + 00
[T] Transportation			
Transport, by tractor	tkm	3.2E + 00	3.2E + 00

Note: For details on data sources and inventory data of tools, please see the supplementary material (Appendix A) provided online.

[a] Emissions calculated with a nutrient balance in the baseline scenario: $P_{emission} = P_{fed}$ - (P_{fed} * $P_{avg.\ retention\ rate}$) and $N_{emission} = N_{fed}$ - (N_{fed} * $N_{avg.\ retention\ rate}$) P and N retention rates of carp were based on findings by Jahan et al. (2003); Jahan et al. (2001); Jahan et al. (2002); Jahan et al. (2000); Watanabe et al. (1999); Watanabe et al. (1987).

[b] Sourced from conventional and organic production, respectively; amount of feed is calculated using the formula: *total weight gain per pond incl. losses at 50% of growth [kg] * FCR*

[c] Only used in scenarios.

3.2. Impact assessment

3.2.1. Comparison of conventional and organic carp farming

The life cycle impact assessment for 1 kg of organic and conventional carp resulted in values differing by a factor of 2–5 between the two products for ME, with 0.01 kg N-eq for conventional and 0.05 kg N-eq for organic carp, TE with 0.2 mol of N-eq for conventional and 0.4 mol of N-eq for organic carp, and AP with 0.05 mol of H^+-eq for conventional and 0.09 mol of H^+-eq for organic carp. The carbon footprint of the two products was 5.98 kg CO_2-eq for conventional and 4.32 of kg CO_2-eq for certified organic carp. Table 4 shows the life cycle impact assessment results clustered in process groups.

A comparison of the environmental impacts of 1 kg of conventional and organic carp shows that organic carp had a lower impact than conventional carp in exactly half of the 14 impact categories (see Fig. 2). Notable are the increases in AP, TE, and ME by 96%, 101%, and 349% respectively, when carp is produced according to organic standards. Over 20% lower impacts for organic carp were found for the impact categories IR_{hh} (−32%), CC (−28%), RD_w (−27%), and OD (−26%).

3.2.2. Identification of significant issues

A contribution analysis to identify the life cycle stages that largely determine the environmental impact of the production of 1 kg of organic and conventional carp revealed that the dominating life cycle stage largely depends on the impact category under consideration (see Fig. 3). Feed and pond dredging played a large role, contributing over 20% in 9 and 8 out of 14 impact categories, respectively. Feed contributed especially significantly to the impact category ME (95% for conventional and 99% for organic carp). This confirms conclusions of previous LCAs of aquaculture products, highlighting feed as fundamental to the environmental impact of the product system (e.g., Henriksson et al., 2011). In order to be able to verify the origin of the increases in ME, TE, and AP for organic carp – impact categories which were dominated by feed use as the main contributor – a separate

Table 4
Life cycle impact assessment results for 1 kg of conventional and organic carp.

Impact Category [Unit]	[A] Carp	[B] Feed	[C] Packaging	[D] Quicklime	[E] Tools	[G] Pond dredging	[H] Mowing	[T] Transportation	Total
AP [mole of H^+-eq]									
Conv.	0.1%	24.8%	0.2%	3.8%	1.2%	55.6%	0.0%	14.1%	4.5E-02
Organic	0.0%	64.5%	0.1%	0.0%	0.6%	28.3%	0.0%	6.4%	8.8E-02
FE_{tox} [CTU_e]									
Conv.	0.0%	34.0%	0.6%	1.9%	7.6%	16.0%	0.1%	39.9%	1.9E+01
Organic	0.0%	48.3%	0.5%	0.0%	6.2%	13.1%	0.1%	31.8%	2.3E+01
FE [kg P-eq]									
Conv.	90.7%	4.6%	0.3%	0.4%	0.4%	2.7%	0.0%	0.9%	6.0E-03
Organic	89.8%	6.0%	0.3%	0.0%	0.4%	2.7%	0.0%	0.8%	6.1E-03
ME [kg N-eq]									
Conv.	0.0%	95.6%	0.1%	0.1%	0.2%	0.4%	0.0%	4.4%	1.1E-02
Organic	0.0%	99.2%	0.0%	0.0%	0.0%	0.1%	0.0%	0.7%	5.1E-02
TE [mole of N-eq]									
Conv.	0.1%	22.5%	0.1%	2.4%	1.0%	59.1%	0.0%	15.3%	2.0E-01
Organic	0.1%	63.4%	0.0%	0.0%	0.5%	29.3%	0.0%	6.7%	4.0E-01
HT_c [CTU_h]									
Conv.	0.0%	41.5%	0.5%	1.9%	5.1%	45.1%	0.1%	5.8%	2.8E-07
Organic	0.0%	31.6%	0.6%	0.0%	6.2%	55.1%	0.1%	6.5%	2.3E-07
HT_{nc} [CTU_h]									
Conv.	0.0%	62.9%	0.4%	2.3%	4.1%	18.0%	0.1%	12.2%	6.6E-07
Organic	0.0%	79.1%	0.3%	0.0%	2.6%	11.2%	0.1%	6.6%	1.1E-06
IR_{hh} [kg U^{235}-eq]									
Conv.	0.0%	31.4%	2.3%	22.8%	4.1%	27.6%	0.1%	11.8%	2.11E+02
Organic	0.0%	33.5%	3.4%	0.0%	6.0%	40.7%	0.1%	16.0%	1.43E+02
CC [kg CO_2-eq]									
Conv.	0.0%	22.1%	0.5%	23.9%	1.5%	40.0%	0.0%	12.0%	6.0E+00
Organic	0.1%	27.1%	0.7%	0.0%	2.1%	55.3%	0.0%	14.8%	4.3E+00
OD [kg CFC-11-eq]									
Conv.	0.1%	16.1%	0.1%	17.2%	0.8%	50.7%	0.1%	15.0%	5.8E-07
Organic	0.1%	11.5%	0.2%	0.0%	1.1%	68.5%	0.1%	18.8%	4.3E-07
PM [kg $PM_{2.5}$-eq]									
Conv.	0.1%	13.0%	0.1%	3.0%	1.1%	64.2%	0.0%	18.5%	4.3E-03
Organic	0.1%	30.2%	0.1%	0.0%	0.9%	54.2%	0.0%	14.3%	5.1E-03
POF [kg NMVOC]									
Conv.	0.1%	9.3%	0.1%	4.3%	1.2%	69.9%	0.1%	14.9%	4.6E-02
Organic	0.1%	10.0%	0.1%	0.0%	1.2%	74.0%	0.1%	14.6%	4.3E-02
RD_{fm} [kg Sb-eq]									
Conv.	0.0%	33.3%	0.1%	1.8%	5.7%	25.5%	0.3%	33.2%	5.9E-05
Organic	0.0%	31.2%	0.1%	0.0%	6.3%	28.2%	0.3%	34.0%	5.3E-05
RD_w [UBP]									
Conv.	0.0%	15.3%	1.8%	10.4%	18.1%	16.5%	0.0%	37.9%	9.2E-01
Organic	0.0%	12.0%	2.4%	0.0%	24.6%	22.5%	0.1%	38.4%	6.7E-01

Note: Indicator values of process groups are displayed as percentages of total. AP: acidification, CC: climate change, FE: freshwater eutrophication, FE_{tox}: freshwater ecotoxicity, HT_c: human toxicity (cancer related), HT_{nc}: human toxicity (non-cancer related), IR_{hh}: ionizing radiation (human health), ME: marine eutrophication, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RD_{fm}: resource depletion (fossil and mineral), RD_w: resource depletion (water), TE: terrestrial eutrophication.

comparison of feed types and their environmental impacts was carried out (see supplementary material, Fig. B1). Comparing the environmental impacts of organic and conventional wheat, barley, and rye grains as well as silage maize, protein peas, and soybeans from cradle-to-farm gate showed that all examined organic crops, except organic soybeans, had a higher AP and TE as well as a higher impact on HT_{nc} and PM, than their conventional counterparts. Wheat, barley, and rye grains also had significantly higher ME and TE, when produced in organic farming systems. The decreased OD and reduced effect on HT_c of all organic crop types, as well as the reduced water use of all crops except barley, were also in line with the impact assessment results of this study for organic and conventional carp.

The carp farming stage itself was accountable for 90% and 91% of FE in organic and conventional carp farming. Mowing, packaging, and the usage of tools contributed very little to the overall impact. The only impact category, where tools played a role was RD_w (25%). AP, TE, HT_c, IR_{hh}, CC, PM, and RD_{fm} were largely dominated by feed use and pond dredging. Pond dredging played an important role for POF (70% for conventional and 74% for organic carp). Transportation contributed over 20% to the impact categories FE_{tox}, RD_{fm}, and RD_w. Furthermore, quicklime played a significant role for IR_{hh} (23%) and CC (24%) in conventional carp farming.

Table 5 shows the results of the sensitivity analysis of using three distinct sets of normalization factors. Values are expressed as the percentage of the normalized value per 1 kg of organic and conventional carp for the process step with respect to the total normalized impact of the reference flows. Equal weighting among impact categories is assumed for this comparison. Pond dredging and feed were again identified as the most significant hot spots.

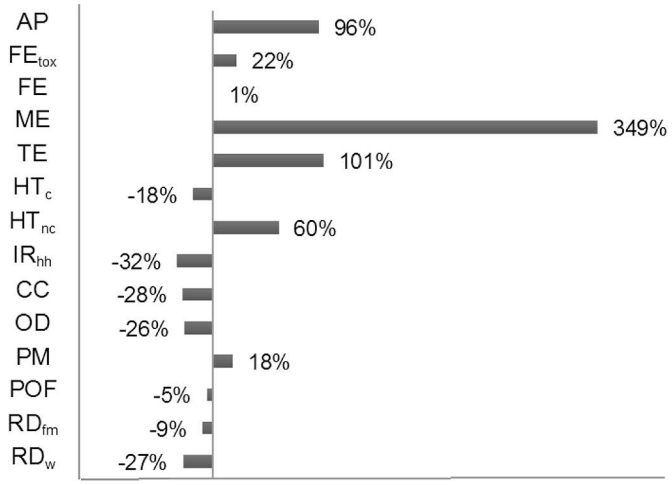

Fig. 2. Impact changes (%) of 1 kg of organic carp in comparison to conventional carp.
Note: read as organic carp has an x% higher impact than conventional carp for positive values and an x% lower impact, for negative values. AP: acidification, CC: climate change, FE: freshwater eutrophication, FE_{tox}: freshwater ecotoxicity, HT_c: human toxicity (cancer related), HT_{nc}: human toxicity (non-cancer related), IR_{hh}: ionizing radiation (human health), ME: marine eutrophication, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RD_{fm}: resource depletion (fossil and mineral), RD_w: resource depletion (water), TE: terrestrial eutrophication.

3.2.3. Outcome of sensitivity analysis

The effect of different sensitivity analyses on the environmental impact categories is illustrated in Table 6. Applying different fertilization scenarios to the model had an effect mainly on three impact categories: ME increased by 157%, when rye was used as green manure (FS3), IR_{hh} increased by 46% and RD_w by 32%, when chicken manure (FS1) was used. FS3 furthermore led to an increase in CC by 15%. Applying wheat straw (FS2) caused only slight increases in HT_c (+19%), ME (+12%), and HT_{nc} (+12%).

The FCR scenarios confirmed the dependence of the overall impact on feed amounts, as changes in FCR were reflected almost one-to-one in many impact categories.

Using the loads of harvesting effluents suggested by Knösche et al. (2000) for ES1 led to a change in only one impact category: FE was reduced by 90.6% in comparison to the use of a nutrient balance, as in the baseline scenario. This underlined the importance of accurate pond effluent modeling and a need for further clarification as to which approach represents a more realistic scenario.

4. Discussion

Many comparative LCA studies face the same challenge: The superiority of one product or production method over the other depends on the impact category analyzed. The same is true for this study. There is therefore no easy answer to the question of which system – conventional or organic – has a greater environmental impact in producing 1 kg of carp. Since the ISO standards do not allow the weighting of impact categories for comparative assertions, i.e., evaluating one type of impact as more important or more environmentally relevant than another, no clear recommendation can be made for or against one of the two production methods. On the other hand, the LCA results – validated by sensitivity analysis and normalization – give insight into differences in the impacts of the two production systems and thereby offer the chance to uncover opportunities to further increase the environmental sustainability of this traditional form of aquaculture. The differences between the two systems are – contrary to public opinion on organic production – overall smaller than expected. The limited difference between the two systems is largely based in their extensive nature, which is very different from – for example – salmonid aquaculture systems that depend much more on external feed supply.

4.1. Environmental sustainability benchmarking

Meaningful comparisons of the environmental impact of different food products need to be based on their common function, which, aside from providing nutritional value, can be described with a variety of indicators for quality, such as taste, shelf life or even emotional value (Schau and Fet, 2007). However, these aspects are not well reflected on a per kg or per ha basis. This provides the first difficulty in LCA benchmarking of food products. Mungkung and Gheewala (2007) propose to normalize the impact indicator value by using the ratio of nutrients gained (per kg) to daily nutrients required, assuming all nutrients to be of equal importance. Schau and Fet (2007) further suggest a quality corrected functional unit on the basis of fat, protein, and carbohydrates. However, these approaches underestimate additional nutritional benefits of fish, such as unsaturated fatty acids, vitamins, and minerals. Furthermore, the analysis, as conducted by Mungkung and Gheewala (2007) resulted in similar trends whether evaluating impacts on a per kg basis or using the new functional unit. Therefore, 1 kg was used as a functional unit for this benchmarking, as a compromise. It should be further noted that comparability across different LCA studies is limited, as system boundaries are usually not defined in exactly the same manner and allocation methods can differ between studies. Therefore, differences in values can only indicate the potential direction of a relative advantage. In addition, not all case studies of aquaculture and agricultural products employ the same methods and categories for impact assessment. Thus, the comparisons in this study are only based on the impact category CC, as carbon footprint studies are the most common (see Fig. 4).

The CC impacts found by this study for organic carp production are in line with those reported by Mungkung et al. (2013) for the production of carp in net cages in Indonesia. In general, recirculating or closed-loop farming has a much higher impact on CC than other aquatic production methods, due to the high energy demand. For example, the energy demand of turbot RASs was five times higher than that of seabass cage systems in the study by Aubin et al. (2009). Ayer and Tyedmers (2009) argue that while closed-containment systems are currently promoted as environmentally friendly forms of aquaculture, due to their ability to reduce local environmental impacts, trade-offs on a global environmental scale, owed to a higher energy demand, are considerable.

While the results of this study, especially for organic carp production, are at the lower end of the scale when compared to the CC impacts reported for other seafood or meat products, it is important to note that an analysis based on only one impact category is not sufficient to make qualified statements about the overall environmental sustainability of a product, as problem shifting, from one impact category to another, may occur. This is well exemplified by RASs, which have much higher impacts on CC and AP, but reduced levels of eutrophication and water usage, when compared to other aquaculture production methods (Aubin et al., 2006; Ayer and Tyedmers, 2009; Samuel-Fitwi et al., 2013).

4.2. Underlying environmental mechanisms

Feed types and amounts play a key role for many of the impact categories evaluated in this study. The differences in ME, TE, and AP between conventional and organic carp can be attributed to differences in feed sourcing. The study by Van Stappen et al. (2015) supports these results: They found organic fertilizer use to be the major contributor to the emissions of organic wheat grains. In their case, NH_3 alone was responsible for 96% of terrestrial acidification and 49% of eutrophication. The authors explain the better performance of

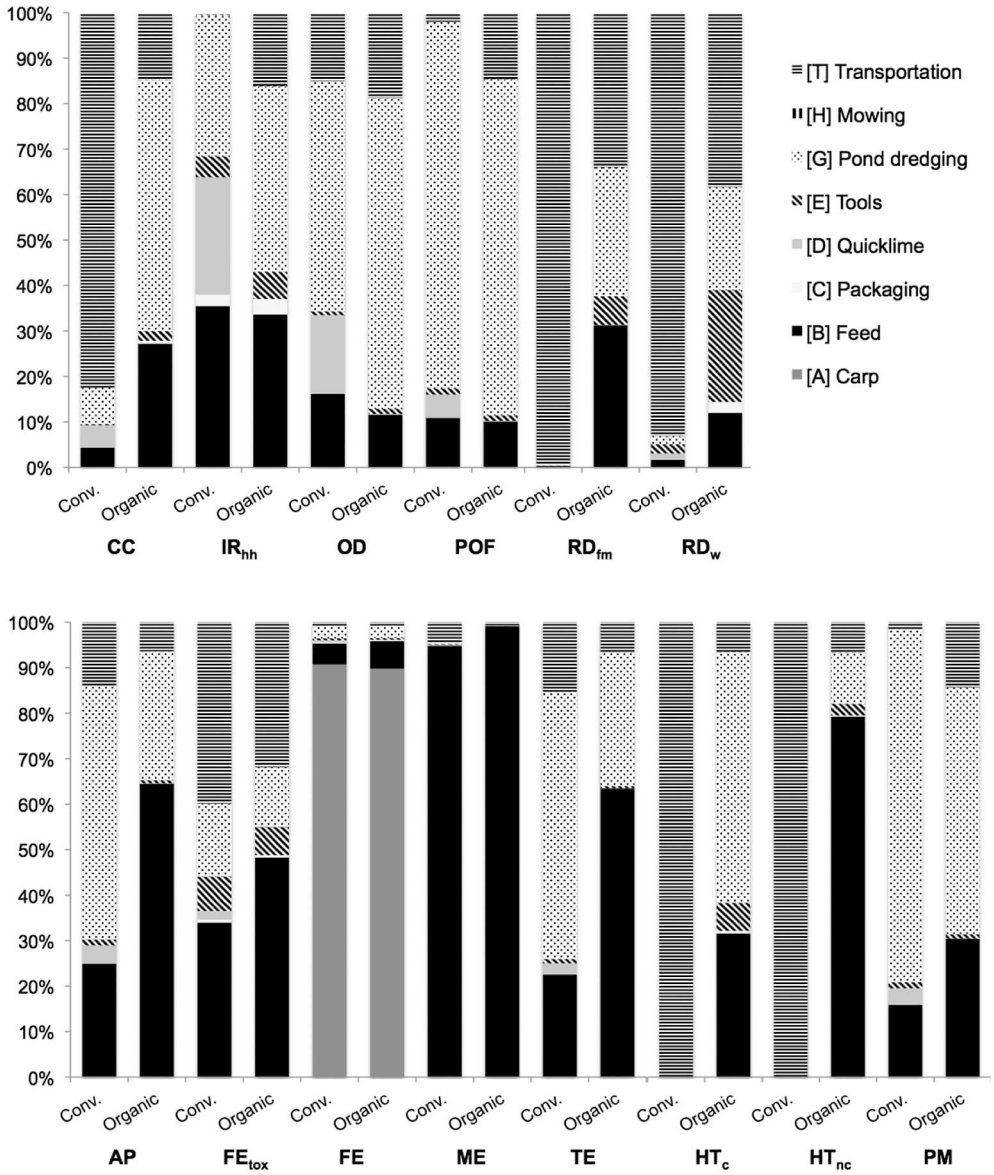

Fig. 3. Contribution analysis of life cycle stages per impact category for 1 kg of conventional and organic carp.
Note: AP: acidification, CC: climate change, FE: freshwater eutrophication, FE_{tox}: freshwater ecotoxicity, HT_c: human toxicity (cancer related), HT_{nc}: human toxicity (non-cancer related), IR_{hh}: ionizing radiation (human health), ME: marine eutrophication, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RD_{fm}: resource depletion (fossil and mineral), RD_w: resource depletion (water), TE: terrestrial eutrophication.

conventional wheat, when comparing the two systems based on a functional unit of 1 kg, with the higher yield per hectare of conventional wheat on the one hand, and the higher impacts of organic fertilizers, due to the higher emission factor of NH_3 volatilization of organic N, on the other hand.

While at first sight, the better performance of conventional carp farming for FE_{tox} and HT_{nc} is surprising, higher toxicity results stem from organic feed crops and were also found in previous studies for organic wheat in Belgium, organic lettuce in Greece, and organic tomatoes in China (Grönroos et al., 2006; He et al., 2016; Meisterling et al., 2009). In these cases, organic fertilizer – the transport and spreading of organic manure as well as the release of heavy metals by organic manures – negatively influenced the environmental sustainability of organic crop production.

The minute impact of mowing, packaging, and tool usage is most likely due to mowing only taking place approximately once per year, little packaging being needed, and tools being used in a sustainable manner for many years by the carp farmers. The low stocking densities of conventional and organic carp can partly explain the large contribution of pond dredging to many of the impact categories: a relatively large pond area has to be cleared per 1 kg of carp during the production cycle. For grower to table-size fish rearing, for example, 3.48 m^3 of pond sediment have to be dredged by heavy machinery per kg of table fish. The relatively limited impact of transportation is most likely due to the regional sourcing of the inputs for carp farming. The higher IR_{hh} and CC impacts of the conventional system can be explained by the use of quicklime, as it contributes 23% and 24% respectively, to the aforementioned impact categories in the conventional system.

Balances of carp ponds are found to be positive on average, meaning that properly managed ponds act as sinks, releasing fewer nutrients than contained in the incoming water (Hlaváč et al., 2015; Knösche et al., 2000). However, during carp harvesting, pond effluents may be released into the environment. The contribution of the carp farming stage to FE (91% for conventional and 90% for organic carp) – measured by the amount of P reaching freshwater end compartments – is attributed to these potential nutrient losses. A reduction of feed as in

Table 5
Comparison of normalization sets for process groups.

	PROSUITE Global per person[a]		EC-JRC EU27 per person[b]		EC-JRC Global per person[c]	
	Conv.	Organic	Conv.	Organic	Conv.	Organic
[A] Carp	2%	2%	0%	0%	4%	5%
[B] Feed	30%	34%	31%	34%	29%	35%
[C] Packaging	2%	3%	2%	3%	2%	2%
[D] Quicklime	20%	0%	22%	0%	17%	0%
[E] Tools	5%	6%	4%	6%	6%	8%
[G] Pond dredging	28%	38%	28%	40%	25%	31%
[H] Mowing	0%	0%	0%	0%	0%	0%
[T] Transportation	13%	16%	12%	16%	18%	20%
Total	100%	100%	100%	100%	100%	100%

Note: Values are expressed as % of the normalized value per 1 kg of organic and conventional carp for each process step, with respect to the total normalized impact of the reference flows. Equal weighting among impact categories is assumed for the comparison.

[a] Laurent et al. (2013).
[b] Benini et al. (2014); Sala et al. (2015).
[c] Benini et al. (2015).

FCRS1 leading to an almost equivalent reduction in FE (48%) can be explained by the interdependence of feed amount and nutrient excess in the nutrient balance calculation. The results obtained for the impact category FE in this LCA should not be over-interpreted since spatial and temporal differentiation has not yet been modeled sufficiently in characterization factors for aquatic eutrophication, especially concerning removal processes for N and P (JRC-IES, 2011). Whether or not increased nutrient loading leads to effects in receiving habitats, such as increased algal growth, changes in species composition, and, ultimately, damage to aquatic ecosystems depends on the site of emission (Seppälä et al., 2004). Depending on N emissions to water, ME is highly influenced by feed use and therefore also reflected in feed reductions almost one to one (49% reduction). TE, depending on NH_x and NO_x emissions to air, also decreases with decreasing feed amounts (12%); however, TE is also largely dependent on pond dredging as well as transportation and therefore less directly affected by a reduction in feed amounts. In relation to the fertilization scenarios, the increase in ME for *FS3* and *FS2* (12% and 157% respectively) is not directly attributable to the carp farming stage, but can instead be explained by the additional N used during the growth of rye and wheat crops. The increase in IR_{hh} for *FS1* (46%) is due to the heavy machinery used to spread the dung on the carp pond surface, as modeled in GaBi.

4.3. Potential for improvement of environmental sustainability

Feed and pond dredging play the greatest role for both product systems, while the carp farming stage is most important for one impact category: FE. Avoiding a loss of nutrients during carp harvest not only decreases the FE potential, but also decreases the necessity to use fertilizers to increase pond productivity. For pond dredging, the recommendation would be to reduce this practice as much as possible. Depending on disease pressure and sedimentation rates, this may not be feasible in all cases. A shift towards longer intervals between pond dredgings (sometimes 20 years and more) is currently already observed in carp farming, due to economic reasons and more extensive production regimes (Wedekind, pers. comm.). Regular trimming of reed to avoid increased sedimentation can be a useful preventive measure. Choosing a type of feed with little environmental impact would have a very large influence on the systems' overall environmental burden. However, advantages shown by other LCAs of different arable crops need to be balanced with further considerations such as transport distance from point of sale, costs, and the quality of the final carp product, achievable with a particular type of feed (Aubin et al., 2009).

4.4. Methodological limitations of LCA

LCA has become a central element of environmental policy-making in the EU, North America, Australia, and parts of Asia (Guinée et al., 2011). Apart from its previously mentioned advantages, LCA also faces methodological challenges. The first and central challenge is that of uncertainty: in relation to the LCI data, choices made in modeling the study, and LCIA methods (e.g., Avadí and Fréon, 2013; Ziegler et al., 2016). Time intensive data collection makes it necessary to use background data from different sources and values without measures of spread, making it hard to judge the overall error of the model (Henriksson et al., 2015). Diverging method choices, such as the setting of system boundaries or LCIA approaches, make comparisons across different studies difficult. Regarding the classification of impacts during LCIA, models of diverging uncertainty are currently used: global indicators, such as climate change, are more robust than site-dependent indicators, such as eutrophication (Ziegler et al., 2016).

LCA generally is not site-specific, thereby not allowing interpretation of results against the backdrop of a certain geographic location (Mungkung and Gheewala, 2007). This was also evident in our study, where e.g. the impact of eutrophication is currently only reflected in a global impact category without local differentiation. The same is true for the impact categories acidification and human toxicity which would

Table 6
Life cycle impact assessment results for 1 kg of conventional carp, under consideration of different fertilization, FCR, and nutrient emission scenarios.

	FS1 Chicken manure		*FS2* Wheat straw		*FS3* Green manure, rye		*FCRS1* FCR = 1		*FCRS2* FCR = 5		*ES1* Knösche et al. (2000)	
AP	4.7E-02	(5%)	4.6E-02	(2%)	4.7E-02	(4%)	3.88E-02	(−13%)	6.3E-02	(40%)	4.5E-02	(0%)
FE_{tox}	2.0E+01	(4%)	2.0E+01	(4%)	2.0E+01	(6%)	1.59E+01	(−17%)	2.9E+01	(52%)	1.9E+01	(0%)
FE	6.0E-03	(1%)	6.0E-03	(0%)	6.5E-03	(8%)	3.13E-03	(−48%)	1.5E-02	(143%)	5.6E-04	(−91%)
ME	1.2E-02	(2%)	1.3E-02	(12%)	2.9E-02	(157%)	5.79E-03	(−49%)	2.8E-02	(147%)	1.1E-02	(0%)
TE	2.1E-01	(4%)	2.0E-01	(2%)	2.1E-01	(4%)	1.74E-01	(−12%)	2.7E-01	(37%)	2.0E-01	(0%)
HT_c	2.9E-07	(4%)	3.3E-07	(19%)	2.9E-07	(5%)	2.17E-07	(−21%)	4.5E-07	(63%)	2.8E-07	(0%)
HT_{nc}	7.0E-07	(6%)	7.4E-07	(12%)	6.9E-07	(5%)	4.44E-07	(−33%)	1.3E-06	(98%)	6.6E-07	(0%)
IR_{hh}	3.1E+02	(46%)	2.1E+02	(1%)	2.3E+02	(7%)	1.75E+02	(−17%)	3.2E+02	(51%)	2.1E+02	(0%)
CC	6.2E+00	(4%)	6.1E+00	(1%)	6.9E+00	(15%)	5.27E+00	(−12%)	8.1E+00	(36%)	6.0E+00	(0%)
OD	6.0E-07	(4%)	5.8E-07	(1%)	6.0E-07	(3%)	5.31E-07	(−8%)	7.2E-07	(24%)	5.8E-07	(0%)
PM	4.4E-03	(2%)	4.4E-03	(1%)	4.5E-03	(3%)	4.04E-03	(−7%)	5.2E-03	(20%)	4.3E-03	(0%)
POF	4.7E-02	(3%)	4.6E-02	(1%)	4.8E-02	(4%)	4.36E-02	(−5%)	5.3E-02	(15%)	4.6E-02	(0%)
RD_{fm}	6.1E-05	(4%)	6.0E-05	(2%)	6.6E-05	(12%)	4.87E-05	(−17%)	8.8E-05	(50%)	5.9E-05	(0%)
RD_w	1.2E+00	(32%)	9.7E-01	(5%)	9.4E-01	(3%)	7.33E-01	(−20%)	1.5E+00	(60%)	9.2E-01	(0%)

Note: Values in parenthesis indicate % change in comparison to the conventional carp baseline scenario. AP: acidification, CC: climate change, FE: freshwater eutrophication, FE_{tox}: freshwater ecotoxicity, HT_c: human toxicity (cancer related), HT_{nc}: human toxicity (non-cancer related), IR_{hh}: ionizing radiation (human health), ME: marine eutrophication, OD: ozone depletion, PM: particulate matter, POF: photochemical ozone formation, RD_{fm}: resource depletion (fossil and mineral), RD_w: resource depletion (water), TE: terrestrial eutrophication, FCR: Feed Conversion Ratio.

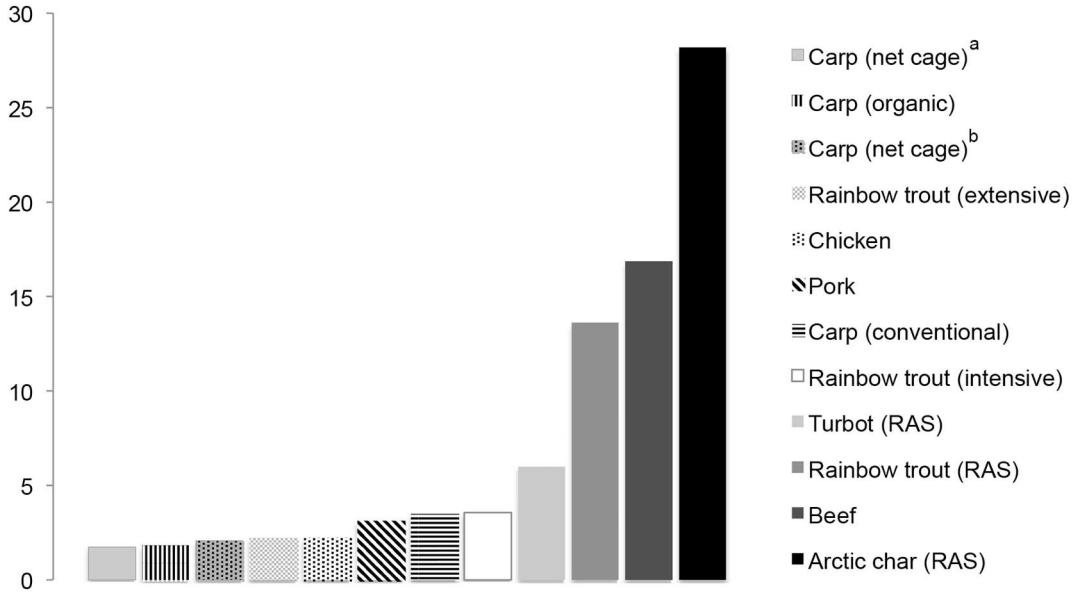

Fig. 4. CC in kg CO_2-equivalents for the production of 1 kg of selected food products.
Note: Values are based on different data sources, therefore no conclusions based on a comparison of absolute values should be made. Tools, transportation, and pond dredging were excluded from the CC impact values for conventional and organic carp of this study, to make results more comparable. For chicken, pork, and beef the CC values for 1 kg of live weight before slaughtering was used. RAS: Recirculating Aquaculture System.
Data Sources: Aubin et al. (2009); Ayer and Tyedmers (2009); Bava et al. (2017); González-García et al. (2014); Mungkung et al. (2013); Ogino et al. (2016); Samuel-Fitwi et al. (2013).
[a] Large farms, high stocking density, [b] small farms, low stocking density, both in Indonesia (Mungkung et al., 2013).

also benefit from a more local applicability. Furthermore, several authors have criticized the lack impact categories specific to LCAs for aquaculture and fisheries (e.g., Mungkung and Gheewala, 2007; Ziegler et al., 2016). Henriksson et al. (2011) and Samuel-Fitwi et al. (2012) suggest new impact categories, such as the destruction of coastal habitats, impacts on the seafloor due to capture fishery for fishmeal and fish oil used in feed, the introduction of invasive species leading to biodiversity loss and genetic pollution, the spread of diseases from farmed fish to wild stock, and socio-economic concerns. While these additional impact categories may be highly relevant for other fish species or production regions, the mentioned issues play only a minor or no role for carp farming in Germany.

Currently, LCA is limited to the assessment of environmental implications. To address this lack of a holistic approach to the sustainability concept, integrating all three dimensions of the triple bottom line – environmental, social, and economic sustainability (Elkington, 1998) – the European Commission developed a framework for Life Cycle Sustainability Analysis (LCSA), which combines LCA with Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA) (Guinée et al., 2011). An integration of further aspects, such as animal welfare, which is taken into account in organic production standards, will further advance the development of a holistic sustainability approach.

In summary, LCA remains the most widely accepted method in the scientific community for quantitative assessments of environmental impacts and with the development of further impact categories as well as general methodological advances, will become even more appropriate for the assessment of aquaculture products.

5. Conclusions

This study evaluated the environmental impacts of conventional and organic carp pond farming, as practiced in southern Germany and many other parts of Europe. The results do not allow for a definitive answer to the question of which system is more environmentally sustainable in producing 1 kg of carp, as the superiority of one over the other depends on the impact category analyzed. The results show only minor differences between conventional and organic carp pond aquaculture. The LCA identified feed and pond dredging – which is already being reduced in current farming practices – as central elements of the impact of carp farming on the environment. This confirms conclusions of previous LCAs of aquaculture products, highlighting feed as fundamental to the environmental impact of the product systems. Feeding management decisions should be based on further LCAs of arable crops, along with efforts to lower the FCR, in order to improve the environmental performance of these production systems. Key drivers of environmental sustainability shown for other fish species produced in pond systems, such as the amount of fishmeal or livestock-derived ingredients used in feed, are already kept to a minimum in carp aquaculture in southern Germany (Nhu et al., 2016). When evaluating fish products, it is important to consider potential trade-offs between different production systems. While capture fisheries and aquaculture are intertwined – with 30–50% of feed for farmed carnivorous species stemming from fisheries – the key environmental impacts of the two production systems stem from quite distinct sources: for seafood it has been shown that GHG impacts are driven by fuel and refrigerant use in fishery, while feed plays a major role in farmed fish (Ziegler et al., 2016). In the case of the analyzed carp production systems shown in this LCA, no direct interaction with capture fisheries occurs, since feed was exclusively comprised of cereals. A comparison with published LCAs of further fish and meat products for the impact category CC shows that both, conventional and organic carp, have significantly lower indicator values than seafood products from RASs and beef. In line with the results of this LCA, Greenpeace and WWF list common carp as the only fish species recommended for consumption without exceptions for different production regions or methods (Greenpeace, 2016; WWF, 2016).

It should be noted that the studied systems may be influenced by the indirect input of fertilizers from adjacent agricultural land, which should be considered in field-based experiments of emissions in follow-up studies. Furthermore, future studies should also take Methane (CH_4) and Nitrous Oxide (N_2O) emissions as well as water loss from evaporation into account (Astudillo et al., 2015; Holgerson and Raymond, 2016; Hu et al., 2012; Panneer Selvam et al., 2014).

In conclusion, efforts to further increase the sustainability of both organic and conventional carp farming should target the key areas of feed type and amount, frequency and method of pond dredging as well as the nutrient retention rate in carp affecting potential emissions during harvest. Moreover, carp products with organic certification, wanting to uphold the claim of superior environmental friendliness, should address the critical issues uncovered in this LCA. We furthermore recommend LCA as a complement to fisheries and aquaculture management tools already in use – such as Management Strategy Evaluation (MSE) – and particularly seafood certification schemes, which currently vary largely in criteria and furthermore do not take a holistic approach to environmental effects throughout the supply chain (Ziegler et al., 2016).

Nhu et al. (2016) suggest that standards certifying environmental and social sustainability are especially relevant for carp, as it can be produced at mass scale with marginal environmental impact. While this may be true for Asia, extensive, small-scale production, as practiced in southern Germany, qualifies for subsidies to promote environmentally friendly products, whether certified or not. Increasing the self-sufficiency of animal protein supply in Europe and the expansion of local aquaculture production close to the point of final consumption, holds further potential for increased environmental sustainability, as refrigerated distribution may contribute disproportionately to the overall environmental impact of highly perishable fish products. Carp is a potential environmentally sustainable solution for supplying future Europeans with fish. For the success of carp on the market, however issues of consumer preference and bias against this fish species have to first be overcome.

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Appendix A. Supplementary data

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